TITLE: A Sweating Agile Thermal Manikin [SAM] Developed to Test Complete Clothing Systems Under Normal and Extreme Conditions

A Sweating Agile Thermal Manikin (SAM) Developed to Test Complete Clothing Systems Under Normal and Extreme Conditions

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Abstract

Moisture transport, thermal insulation and their interaction influence both the comfort and protective properties of clothing systems. Depending on the environmental conditions and clothing design, wind and repetitive body movements can increase the transport of heat and moisture away from the body. Thus a thermal manikin designed to test clothing realistically, particularly under extreme conditions, should be able to sweat and perform such movements.

SAM is a newly developed thermal manikin capable of simulating even heavy work conditions, with sweat rates of up to 4 litres per hour and human movements such as walking and climbing. The anatomically-formed body is divided into 30 sectors, each heated separately with its own average surface-temperature sensor. In total 125 sweat outlets are distributed over the body surface, with which both vapour and liquid sweating can be simulated over all the body or just chosen parts. SAM is designed to operate at temperatures between –30 and 40°C, with relative humidities ranging from 30 to 95% and up to high wind speeds.

SAM compliments the existing array of sweating body-part simulation systems at EMPA, such as the sweating head ALEX and the sweating torso, by adding the capability of measuring whole-body clothing systems under realistic reproducible conditions and reducing the need for expensive human tests.

Introduction

Thermal manikins are used to help evaluate the comfort and safety properties of clothing. They approximate the thermal nature of the human body and bridge the gap between simple systems to measure thermal resistance (R_{ct}) and water vapour resistance (R_{et}) and the human being, with his repertoire of complex control and sensory systems.

Over the past 16 years EMPA has developed and built a range of increasingly complex body-part systems to measure the thermal resistance of clothing layers with and without the influence of simulated sweat. In 1985, EMPA started to measure R_{ct} and R_{et} separately using the Hohenstein skin-model [1] and developed this to study the influence of rain on R_{et} [2]. This was followed by a heated non-sweating hand, which was built in 1989 to test gloves primarily in cold environments [3]. The sweating arm, built in 1993, is able to sweat and perform simple forearm movements [4]. Shortly afterwards in 1995, the sweating Torso was built to simulate the human trunk [5, 6]. The sweating head (1999) is built to measure the physiological properties of helmets [7]. Finally, following almost 5 years of development, construction of the sweating agile manikin (SAM) was completed this year. A more detailed description of SAM is given elsewhere [8].

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Traditionally thermal manikins are used to measure the thermal insulation of clothing systems without the presence of body moisture [9]. However body moisture is always present within clothing system layers and effects the total effective thermal insulation.

More recently a handful of thermal manikins have gained the ability to sweat. However the design of the sweating system used and the analysis of results have not yet been standardised [10]. As the newest addition to these sweating thermal manikins, SAM offers a novel internal sweating system, which produces vapour sweating only to simulate insensible human sweating when at rest and combined vapour and liquid sweating to simulate sensible human sweating at high work loads. Although several manikins have moveable joints, or even simple sinusoidal drive mechanisms, the eight-axis drive system of SAM enables even complicated 2-D movements of each limb. Thus realistic human movements can be simulated.

Background

Humans have a complex thermoregulatory system which, under normal conditions, is able to keep the vital organs such as heart, lungs and brain within a narrow temperature band around 37°C. The body produces heat through metabolic processes such as digestion and muscular activity. Depending on the climatic conditions and the clothing worn, excess heat is lost by evaporation, radiation, conduction and respiration.

When the body starts to cool down due to insufficient food, exercise and/or clothing insulation in a cold climate, the body increases its own thermal insulation by reducing the flow of blood to the skin surface, particularly at the extremities. As the sweat rate is also reduced to a minimum (20-25 ml / h, insensible sweating), the heat flow from the body is minimised. Additionally shivering (involuntary muscular contractions) can produce compensatory energy of up to 450 W [11]. Normally the loss of heat through breathing accounts for 10% of the total heat loss, but can increase to as much as 30% in cold climates.

When the body starts to overheat, vasodilatation allows warm blood to flow near to the skin's surface over the whole body to maximise the heat flow from the body particularly from the extremities. Additionally the overall rate of sweating increases. If this sweat is able to evaporate, the body losses additional heat. The evaporation of 1 litre of sweat causes a heat loss of about 670 Wh. Over short periods of time, up to 4 litres per hour can be sweated [12].

Soldiers who need to wear or carry protective clothing for long periods of time may also be subjected periodically to heavy workloads. Protective properties against wind, rain, certain liquids, heat, flame, thorns, rocks, shrapnel, and nuclear, biological and chemical weapons (NBC) all tend to increase the impermeably to water vapour. Thus not all the body moisture can escape to the external environment. Over a long period of time the moisture content can build up, which reduces the overall thermal insulation (e.g. [6]). In cold climates, the insulation is ideally a maximum when at rest and a minimum whilst working hard.

Body movements tend to reduce the thermal insulation of clothing systems due to increased exchange of air between the clothing layers (microclimate) and the external environment [13]. For certain clothing systems the thermal insulation reduces exponentially with increased walking step frequency and exponentially with increased wind speed [14]. High wind speeds can press the clothing layers together, reducing the insulating air layers and thus the insulation considerably. Additionally wind may flow through the clothing. For example, figure 1 shows that an increase of wind speed from 1 to 13 m/s can reduce the effective thermal resistance by up to 80% for fleece materials. For some protective (e.g. NBC) suits where openings at the wrists, ankles and neck are closed, the air cannot exchange directly and any moisture must pass through the clothing layers or breathing apparatus.

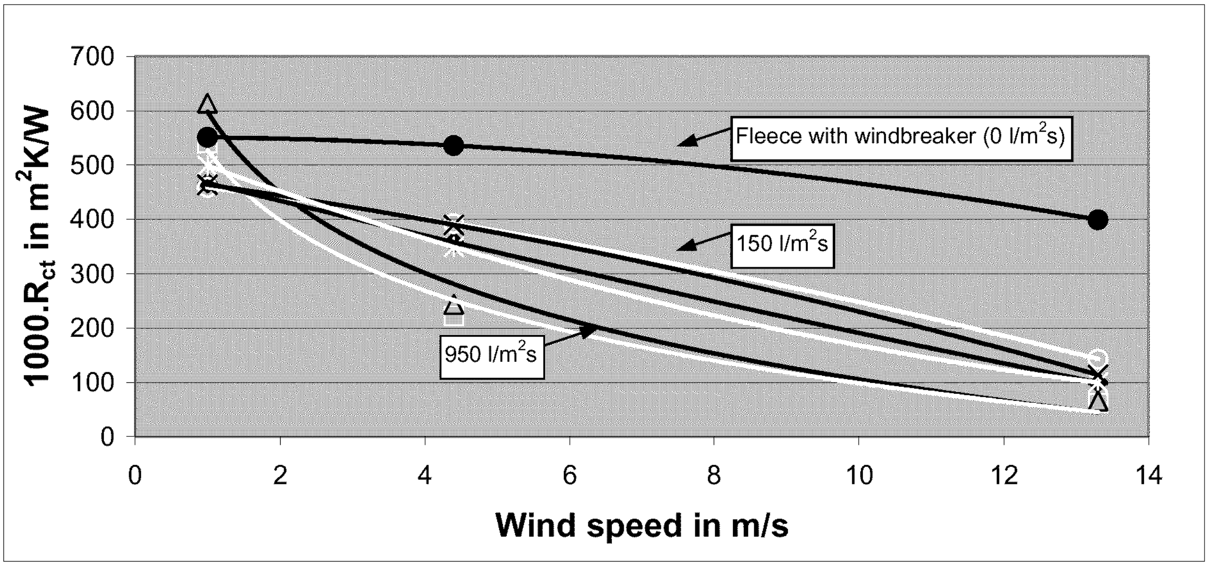

Figure 1 Reduction of thermal resistance with wind speed for various fleece materials measured on the sweating arm. The air permeability is given for three fleeces.

As well as being costly, human tests of clothing systems produce results with poor reproducibility, with results being dependant on many factors including the person being tested, sex, age, diet, sleep pattern, time of day and the activity prior to each test. Furthermore practice tests must often be carried out under medical supervision. Under extreme conditions practice tests can also be dangerous and may even be forbidden by law. By using a thermal manikin, such tests can be performed without the possible risk to life.

Measurement systems built to simulate the human body or body parts produce results with a high reproducibility, but no direct information on subjective human responses such as comfort and pain.
By using a combination of human and system tests, clothing systems can be studied from both psychological and thermal aspects.

SAM's heated sectors

The surface of SAM is divided into 30 separate uniformly-heated sectors (Figure 2). Each sector can be heated at a constant average surface temperature or with a constant power. Thus the whole surface can be heated to a constant temperature to perform standard ISO TC 38 WG17 measurements of thermal insulation or supplied with different heating powers to simulate various activities. A total heating power of up to 1.2kW can be supplied, simulating a very high physical activity as performed by a top sportsman.

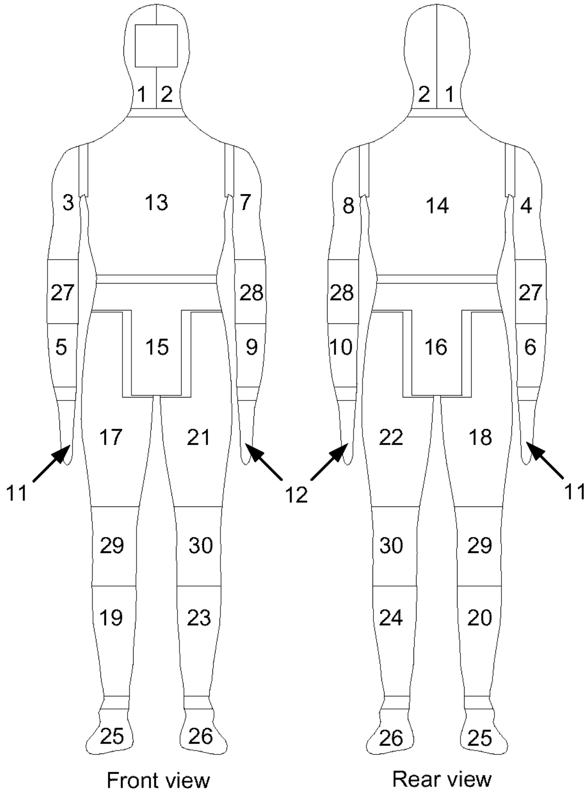

Figure 2 The 30 separately-heated sectors of SAM

Sweating system
SAM has 125 sweat outlets distributed over its surface. Although the human skin has millions of sweat glands, the outlets have been positioned to ensure a sweat distribution roughly similar to the human. Distilled water is used to simulate sweat, supplied through SAM's face to internal valves, which are used to regulate the flow. Special pads which cover the outlets ensure that all the water evaporates at low sweat rates simulating insensible sweating and both vapour and liquid water are output at higher sweat rates to simulate sensible sweating. The total sweat rate is determined with a balance from the reduction of water in the supply tank external to SAM. The total amount of moisture within the clothing is determined by monitoring SAM's weight. The sweat rate can be varied from 20 ml/h up to at least 4 litres per hour to simulate all possible activities and conditions.

Realistic movement system
Much effort has been made to ensure that SAM can perform realistic movements. Joints at the shoulders, elbows, hips and knees enable each limb to be moved in a vertical plane. Each limb is connected to a 2-axis linear drive mechanism. Thus repetitive body movements such as walking and climbing can be performed during an active test phase. Figure 3 shows SAM walking at 2.5 km/h.

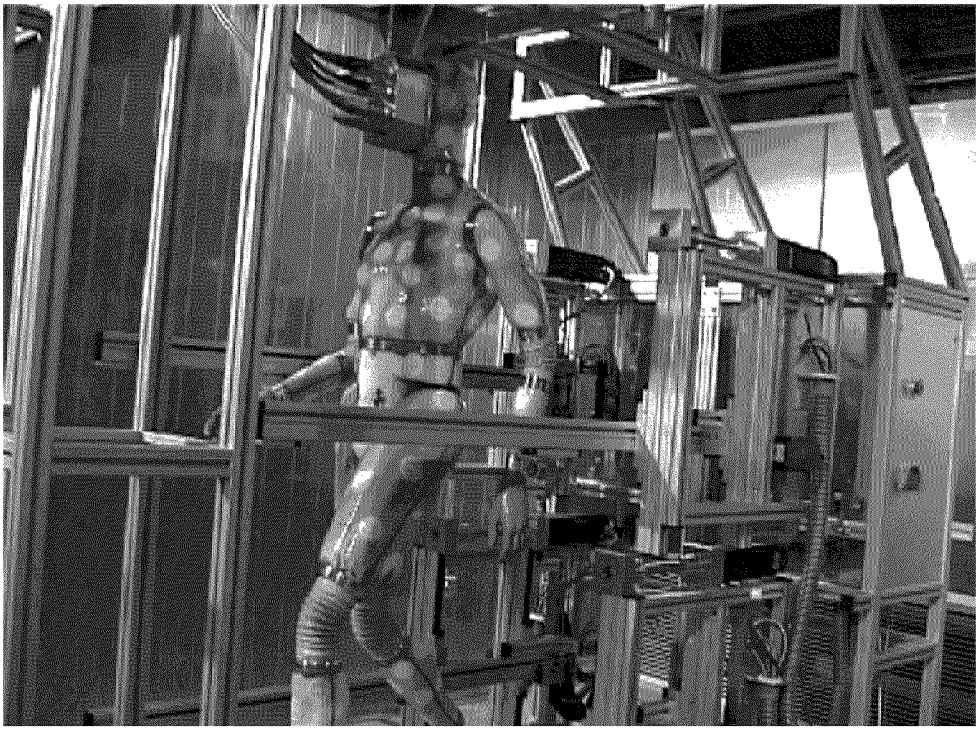

Figure 3 SAM walking unclothed at 2.5 km/h.

Measurements techniques

SAM is positioned in a climatic chamber designed to operate at temperatures between –30 and 40°C, with relative humidities ranging from 30 to 95%. A wind generator provides winds up to high speeds and snow and rain can be simulated additionally.

Measurements of the sweat rate and average surface temperature of and average power supplied to each sector are recorded each minute. The total condensate within the clothing is measured at regular intervals. Up to 8 additional sensors (e.g. temperature, humidity, friction etc) may be added to SAM. External temperature and relative humidity sensors are positioned between clothing layers to determine the partial water vapour pressure within the microclimate.

Validation tests

In order to compare the results of SAM directly with the reality, a series of human tests involving 20 young male subjects and 9 different clothing systems has been carried out. As each subject tested each clothing system at least 3 times, over 540 test were performed in total. These tests were divided into 3 categories of different clothing systems representing different physiological loads (Table 1). The first three clothing system results have been presented previously [15]. Results of these human tests will be compared to those of the same clothing systems measured using SAM.

Clothing system		Conditions				
Nr.	Description	T [°C]	r.H. [%]	v_A [m/s]	R [kW/m^2]	M [W]
1.1	Fire-fighter's clothing with compact coating	30	50	2	0.5	350
1.2	Breathable fire-fighter's clothing	30	50	2	0.5	350
1.3	Fire-fighter's station wear	30	50	2	0.5	350
2.1	Clothing for work by temperatures at –20°C	-20	---	2	---	350
2.2	Clothing for work by temperatures at 0°C	0	---	2	---	350
2.3	Clothing for work at room temperature	20	65	2	---	350
3.1	Combat clothing with NBC protection	20	50	2	---	350
3.2	Combat clothing with rain protection	20	50	2	---	350
3.3	Combat clothing with T-shirt	20	50	2	---	350

Table 1 Human tests performed to validate SAM

Discussion

Using steady-state measurements of a thermal manikin, values of effective R_{ct} and R_{et} can be obtained. However in reality humans must perform varying activities in varying climatic conditions. Therefore dynamic responses are also of interest, particularly when predicting the permissible exposure time or survival time under extreme conditions, where the skin and core temperatures are decisive.

As SAM does not have a thermoregulatory system such as the human being, this would need to be simulated using an appropriate control algorithm in order to obtain a similar dynamic response. Such an algorithm must account for the missing blood flow, thermal capacity and breathing. The human body uses a combination of core and skin temperature sensors to regulate blood flow and sweat rate. As SAM does not have an equivalent to core temperature, this may prove to be difficult. Furthermore the distribution of sweat on SAM's surface is only approximate to the human's and relies partly on wicking in the innermost clothing layer. It is planned to model the behaviour of SAM using 3-D computational modelling.

In spite of the differences between SAM and the human body, SAM is capable of comparing different clothing systems under identical conditions and measuring differences in clothing design and manufacture by changing climate and body activity.

Due to the unavoidable spread of physiological data obtained from human tests, tests must be designed to have sufficient physiological load to demonstrate any significant differences when comparing two or more clothing systems. As simulation systems such as SAM produce more repeatable results, even small differences may be significant and small improvements in clothing may be measurable.

Conclusions

Human subject tests of clothing systems are prone to be inaccurate due to variations in human response to even a well-defined scenario. Sweating thermal manikins such as SAM are designed to simulate the human body in terms of heat production, sweat production and movement as closely as possible. Such simulation systems produce results which have a much higher repeatability than those from practice tests, enabling even small differences in clothing to be observed. As a thermal manikin can never truly mimic the human, thermal manikin results should only be interpreted as approximate or indicative or used for relative tests of different clothing systems. Limitations of design such as missing thermal capacity, blood flow control and thus a missing core temperature may be overcome by suitable models. SAM will be capable of comparing the relative dynamic response of clothing systems to body heat, sweat and movement over a large range of environmental conditions, without the inherent costs of human tests and the possible risk to life.

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References

[1] ISO 11092 (1993) *Textiles - Physiological effects - Measurement of thermal and water-vapour resistance under steady-state conditions (sweating guarded-hotplate test)*

[2] Weder M (1990) *Wasserdampfdurchgang an Regenschutzbekleidung auch unter Beregnung?* Textilveredlung 1, 31-34

[3] Kurapkat J (2000) *Handgemacht: 37 Handschuhe im Test* Outdoor Magazine 1/2000, Rotpunkt, Germany

[4] Weder M S, Zimmerli T and Rossi R M (1995) *A sweating and moving arm for the measurement of thermal insulation and water vapour resistance of clothing* Performance of Protective Clothing: 5th Volume, ASTM STP 1237, James S Johnson and S Z Mansdorf, Eds. American Society of Testing and Materials

[5] Zimmerli T and Weder M S (1997) *Protection and Comfort – A Sweating torso for the simultaneous measurement of protective and comfort properties of PPE* Performance of Protective Clothing: 6th Volume, ASTM STP 1273, Jeffrey O Stull and Authur D Schwope, Eds., American Society for Testing and Materials

[6] Camenzind M, Weder M and den Hartog E (2001) *Influence of Body Moisture on the thermal insulation of sleeping bags* Blowing Hot and Cold: Protecting against Climatic extremes, HFM Dresden

[7] Hering A M, Weder M S, Richards M G M, Mattle N G, Camenzind M, Derler S and Huber R (2001) *Evaluation of physiological properties of motorcycle safety helmets using a new sweating thermal head manikin* Proceedings of the 4th International Meeting on Thermal Manikins, 4IMM, Richards, Ed., EMPA, Switzerland

[8] Richards M G M and Mattle N G (2001) *Development of a sweating agile thermal manikin (SAM)* Proceedings of the 4th International Meeting on Thermal Manikins, 4IMM, M Richards, Ed., EMPA, Switzerland

[9] Holmér I (1999) *Thermal manikins in research and standards* Proceedings of the 3rd International Meeting on Thermal Manikin Testing, H Nilsson and I Holmér , Eds., Arbeite och Hälsa, NIWL, Sweden

[10] McCullough E (2001) *Interlaboratory Study of Sweating Manikins* Proceedings of the 4th International Meeting on Thermal Manikins, 4IMM, M Richards, Ed., EMPA, Switzerland

[11] Schmidt R F, Thews G and Lang F (2000) *Physiologie des Menschen* 28th ed. Springer

[12] Aschoff, J., Günther, B. and Kramer, K. (1971) *Energiehaushalt und Temperaturregulation* (Urban & Schwarzenberg, München).

[13] Kim, C S and McCollough, E A (2000) *Static and Dynamic Insulation values for cold weather protective clothing*, Performance of Protective clothing for the 21st century: 7th volume, ASTM STP 1386, C N Helson and N W Henry, Eds, American Society for testing and materials, West Conshohocken, PA

[14] Nilsson and Holmér (1997) *Development of clothing measurement methods with the thermal manikin TORE*, 5th International Symposium on Protective clothing (NOKOBETEK 5), Elsinor Denmark

[15] Richards M G M (2000) *Physiological studies of humans wearing fire fighter clothing systems for the validation of a sweating manikin* Proceedings of the 9th International Conference on Environmental Ergonomics 2000:07, 401-404